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The purpose of this study was to evaluate the newly constructed environmental stress index (ESI) for a large database consisting of various climatic conditions. This index was applied to database measurements from 19 various locations. Data analysis revealed high correlation between ESI and the wet bulb globe temperature (WBGT) index for each of the databases from the 19 different locations. However, validity from statistical analysis, including optimization procedures, slightly changed the ESI constants as follows:

$$ESI = 0.62Ta - 0.007RH + 0.0002SR + 0.0043(Ta \cdot RH) - 0.078(0.1 + SR) - 1$$

where: Ta = ambient temperature (°C); RH = relative humidity (%); and SR = solar radiation (W.m⁻²). This new refined index and the WBGT index were applied to databases of more than 126,000 measurements for each variable [Ta, RH, SR, black globe temperature (Tg), and wet bulb temperature (Tw)]. ESI was then successfully correlated with WBGT for each of the 19 different databases (P < 0.05, R² > 0.899). Therefore, it is concluded that ESI, which is constructed from fast response and commonly used weather sensors (Ta, RH, SR), is a potential index to serve as an alternative to the WBGT for heat category assessment.

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MEMORANDUM FOR Commander, U.S. Army Research Institute
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1. The enclosed technical paper has been reviewed.
2. The technical paper is approved for publication in the European Journal of Physiology.
3. Point of contact for this action is Ms. Kristin Morrow, DSN 343-7327 or by email at kristin.morrow@det.amedd.army.mil.

FOR THE COMMANDER:

Encl

Phyllis Rinehart
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Information Management

Evaluation and refinement of the environmental stress index (ESI) for different climatic conditions

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Running head: ESI evaluation



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Abstract

The purpose of this study was to evaluate the newly constructed environmental stress index (ESI) for a large database consisting of various climatic conditions. This index was applied to database measurements from 19 various locations. Data analysis revealed high correlation between ESI and the wet bulb globe temperature (WBGT) index for each of the databases from the 19 different locations. However, validity from statistical analysis, including optimization procedures, slightly changed the ESI constants as follows:

$$ESI = 0.62T_a - 0.007RH + 0.0002SR + 0.0043(T_a \cdot RH) - 0.078(0.1 + SR)^{-1}$$

where: T_a = ambient temperature ($^{\circ}\text{C}$); RH = relative humidity (%); and SR=solar radiation ($\text{W}\cdot\text{m}^{-2}$). This new refined index and the WBGT index were applied to databases of more than 126,000 measurements for each variable [T_a , RH, SR, black globe temperature (T_g), and wet bulb temperature (T_w)]. ESI was then successfully correlated with WBGT for each of the 19 different databases ($P < 0.05$, $R^2 \geq 0.899$). Therefore, it is concluded that ESI, which is constructed from fast response and commonly used weather sensors (T_a , RH, SR), is a potential index to serve as an alternative to the WBGT for heat category assessment.

Keywords: heat-stress, indices, solar radiation, relative humidity

Introduction

Heat stress evaluation is generally determined through meteorological parameters that enable one to estimate the influence of several environmental factors on thermal comfort and physiological ability. The variables included in heat stress indices and their relative weights have changed over the years. Haldane (1905) developed an index for heat load and claimed that changes in the wet bulb thermometer alone were enough to integrate global heat load. Other environmental indices have also been suggested which include measurement of airflow and thermal radiation. Hill et al. (1916) introduced the "Kata" thermometer, which enabled measurement of heat dissipation as a function of wind speed and other parameters. In 1932, Vernon was the first to integrate radiant heat into an environmental stress index by using the globe thermometer.

Yaglou and Minard (1957) first introduced the wet bulb globe temperature (WBGT) during an extensive period of development of heat stress indices in the first half of the 20th century. The WBGT index was well received mainly because of its simplicity and convenience of use and soon was considered the most common heat stress index for describing environmental heat stress. This index is obtained from three parameters: black globe temperature (T_g), which considers the solar radiation; wet bulb temperature (T_w); and dry bulb temperature (T_a), and it is calculated as follows: $WBGT = 0.7T_w + 0.2T_g + 0.1T_a$. WBGT has gained immense popularity over the years and has been in use in the field by the U.S. Army. It is the index on which sports associations base training safety orders as guidance to prevent heat injury (American College of Sports Medicine 1996; Burr 1991; McCann and Adams 1997; Montain et al. 1999; Moran and Pandolf 1999). The World Health Organization (WHO) has also adopted it. In 1972, the National Institute for Occupational Safety and Health (NIOSH) established the WBGT as the criterion for determining occupational exposure to a hot environment. In 1982, WBGT was approved by the ISO as an

international standard for heat load assessment, and it is commonly used as a safety index for workers in various occupations (Chaurel et al. 1993; Froom et al. 1992; Gun and Budd 1995; Singh et al. 1995). Later, work-rest regime regulations were made based on this index. However, inherent limitations of the WBGT have been reported (Gonzalez et al. 1985; Matthew et al. 1986) in terms of applicability across a broad range of potential military scenarios and environments. WBGT is limited in its evaluation of heat stress due to the inconvenience of measuring T_g . The T_g is usually measured by a thermometer surrounded by a 6" blackened sphere, and purportedly integrates the global radiation component of the thermal load. However, measuring T_g is cumbersome in many circumstances for two main reasons. First, T_g measurement requires about 30 min for the instrument to reach equilibrium. Second, the blackened sphere is often too large for specialized spaces like helicopter cockpits or armored vehicles. Therefore, measuring T_g becomes impractical, especially in transient situations.

At the time WBGT was introduced, many empirical indices were developed that originated from the old effective temperature (ET), the corrected ET (CET), the modified ET (MET), and the equivalent ET (ETR) (Bedford 1980; Majumdar 1978; Yaglou 1927). All of these indices were based on T_a , T_w , and T_g , but none was ever associated with any physiological variable. The WBGT has been only partly evaluated by analyzing the association between heat stroke cases in soldiers and the heat load assessed by the WBGT (Yaglou and Minard 1957). In fact, there is no known laboratory- controlled study where the WBGT was evaluated. In 2001, Moran et al. (2001a) introduced a new environmental stress index (ESI) based on measurements of T_a , relative humidity (RH), and solar radiation (SR). ESI was highly correlated with the WBGT index (Moran et al. 2001a). The ESI as a stress index, for the first time, incorporates direct measurements of SR and RH (Moran et al. 2001b). Additionally, all the three meteorological variables that make up the ESI are

characterized by fast reading sensors easily obtained commercially. Recently, ESI was further evaluated for the physiological strain index (PSI) and for different physiological variables that reflect physiological strain including core temperature, heart rate, and sweat rate (Moran et al. 2002).

The purpose for the present study was to evaluate and validate, using a large database, the ESI and to assess and determine whether this newly developed index can serve as a reliable and valid alternative to WBGT for measuring environmental stress.

Materials & Methods

The database was obtained from a study collected at various climatic sites in Israel and contained 126,558 measurements for each of the variables measured. Weather measurements were collected every 10 min, 24 hours a day, for 120 days, at 19 different locations around Israel, including sites near the Mediterranean Sea, characterized as a high humidity zone; sites in the desert, characterized as a hot/dry zone; and sites near the Red Sea, characterized as an extremely hot/dry zone. The collected meteorological measurements were used to calculate WBGT, which served as the gold standard, and ESI.

Measurements: The official Israeli Meteorological Service collected weather measurements for the nineteen locations. T_a and T_w were measured with Campbell thermometers (model HMP45C), and relative humidity (RH) was measured with a Rotronic instrument (model, MP 100A). These three instruments were placed under a shelter (Stevenson screen). Under open sky, T_g was measured using the Vernon black globe thermometer; solar radiation (SR) was measured using the EPLAB radiometer (sensitivity of 285-2800 nm), and the infra-red (IR) light sensor measured by Centro Vision sensor (model CD-1705) with peak sensitivity of 800-920 nm.

Calculations

Heat stress indices were calculated as follows: WBGT was calculated according to Yaglou and Minard's standard formula (1957); $WBGT = 0.7T_w + 0.2T_g + 0.1T_a$. The ESI was first calculated as originally published as follows (Moran et al. 2001a):

$$ESI = 0.63T_a - 0.03RH + 0.002SR + 0.0054(T_a \cdot RH) - 0.073(0.1 + SR)^{-1}$$

However, as an outcome of this study, ESI's constants were changed to better reflect correlation with WBGT.

Statistical analysis

For the evaluation of the modified ESI, we validated a series of models for WBGT as dependent variables, and T_a , RH, SR, their interactions and different transformations (inverse, and quadratic) as independent variables. Pearson's analysis was used for testing bivariate correlations between the independent and the dependent variables. All models were linear models and used the least squares algorithm. Optimization of the constants was executed by the DUD (does not use derivative) method (Ralston and Jennich 1978). For all models, we computed the coefficient of determination (R-Square of the model) and plotted a series of residual plots versus predicted values for all data and for every meteorological station separately. All statistical contrasts were accepted at the $P < 0.05$ level of significance. Data are presented in this study as means \pm SE. For all computations and statistical analysis, we used SAS 8.0 Software, Procedures CORR and GLM.

Results

These data were collected every 10 min over 24 hr for 120 days from 19 meteorological stations. Therefore, a wide range of weather measurements, over 126,000 for each variable, was covered (Table 1). The WBGT and ESI were applied and analyzed for correlation for each of the different 19 stations. However, for statistical analysis and clarified

presentation, the collected data were pooled for 2 groups of 9 and 10 meteorological stations each.

PLEASE INSERT TABLE 1 ABOUT HERE

The analysis between ESI and WBGT values, obtained from the same 10 and 9 sites, is presented in Figures 1 and 2 for correlations (bottom panel) and residual scattergram (top panel). For both of these 2-pooled groups, high correlations ($R^2=0.975$ and 0.963 for Figs. 1 and 2, respectively) were found. However, in order to better correlate ESI with WBGT and to try to improve the distribution around the line of identity, we evaluated anew the ESI construction.

PLEASE INSERT FIGS. 1-2 ABOUT HERE

The ESI evaluation was based on statistical analysis, which included three steps. The first step applied the original ESI to the 19 different databases and analyzed them for correlation between WBGT and ESI, and the residual scattergram from the line of identity. In the second step, we validated the WBGT as a dependent variable, and each of the variables (T_a , RH, SR) and components in the original ESI as an independent variable. Since the results from the second step revealed a very high correlation between the dependent and the independent variables, we progressed to the third step. For the third step, we optimized the different constants of the ESI variables, interaction and transformation as follows:

for T_a measured in $^{\circ}\text{C}$:

$$\text{ESI}=0.62T_a-0.007\text{RH}+0.002\text{SR}+0.0043(T_a\cdot\text{RH})-0.078(0.1+\text{SR})^{-1}$$

for T_a measured in $^{\circ}\text{F}$:

$$\text{ESI}=0.73T_a-0.007\text{RH}+0.005\text{SR}+0.0026(T_a\cdot\text{RH})-0.115(0.1+\text{SR})^{-1}$$

The modified ESI was applied separately to each of the 19 databases, and overall, a highly significant correlation coefficient ($R^2 \geq 0.898$, $P < 0.001$) was obtained with residuals distributed symmetrically around the zero line in most of the locations. A comparison of the modified ESI with the WBGT pooled into 2 groups of data obtained from 10 and 9 different sites are depicted in Figures 3 and 4, respectively.

PLEASE INSERT FIGS. 3-4 ABOUT HERE

Discussion

The modified ESI introduced in this study to evaluate environmental heat stress reliably matches values calculated by using the conventional WBGT. This modified ESI is based on the same parameters as the original ESI (T_a , RH and SR), which integrates the thermal load derived by the specific climatic conditions. However, separate analysis of the 19 different databases obtained from the 19 different locations revealed changes in the ESI constants of the variables, interaction, and transformation. Arithmetically, the first developed ESI was well correlated to WBGT (Moran et al. 2001a). However, validation of the modified ESI for these large databases further improved the correlation with the WBGT. The strength of any prediction index is its ability to predict with high correlation the measured or calculated universal index under widely varied climatic conditions. Thus, the 10 and 9 databases pooled into 2 groups revealed with very high correlation between ESI and WBGT ($R^2 = 0.980$ and 0.964 , respectively).

ESI differs from other indices that have been suggested in the past in two critical ways. First, this stress index for the first time uses direct measurements of SR and RH. These direct measurements of SR and RH, when used in ESI, are not as cumbersome as the measuring of T_g and T_w for calculating the WBGT. Second, the three meteorological variables used in ESI are characterized by fast-reading responses that take only a few seconds

to reach equilibrium. For an index to be valid and practical, it should allow the comparison and evaluation of a combination of different meteorological parameters as far as their influence on the individual is concerned. It also helps to find different combinations of these parameters that cause equal subjective heat sensations. Moreover, the index must enable one to assess the different weights of each of the meteorological parameters on the individual (Givoni and Goldman 1972).

This study separately confirms the results of previous study (Moran et al. 2001), which initially introduced ESI and found a high correlation with WBGT. However, in the present study, ESI was evaluated using a larger database with revised constants included in its determination and a higher correlation with WBGT. In a recent study (Moran et al. 2002) ESI was evaluated with the physiological strain index (PSI) and for 3 independent physiological variables (rectal temperature, heart rate, and sweat rate) under different combinations of metabolic rates, clothing and solar radiation. The high correlations ($R \geq 0.838$) found after 120 min between these two indices and between ESI and these physiological variables can also serve as a validation for ESI that previously was validated only for other stress indices [WBGT and the discomfort index (DI)]. Therefore, the ESI has the potential to serve as a substitute to the WBGT index and to be used for safety limits during training and military activity. It can also serve as a part of the guidelines for work rest cycles and fluid replacement. However, further evaluation studies between ESI obtained from different climate conditions and physiological variables measured at different metabolic rates are essential for the usage of ESI universally.

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Table 1. Mean (\pm SD) and range of environmental measurements of the ESI validation versus the WBGT. Data were collected from 19 different locations every 10 min over 24 hours for 120 days.

	T_a	T_w	RH	T_g	SR	WBGT
	(°C)	(°C)	(%)	(°C)	(W·m ⁻²)	(°C)
Mean \pm SD	23.07 \pm 6.35	16.88 \pm 3.66	55.52 \pm 24.00	26.40 \pm 10.81	289 \pm 353	19.05 \pm 4.71
Range	0.80-44.30	0.60-29.70	1.75-100	0-59.42	0-1337	0.7-32.58

FIGURE LEGENDS

Figure 1: Comparison of the original ESI with the WBGT index obtained from 10 different locations showing correlation (bottom) and residuals (top).

Figure 2: Comparison of the original ESI with the WBGT index obtained from 9 different locations showing correlation (bottom) and residuals (top).

Figure 3: Comparison of the revised ESI with the WBGT index obtained from 10 different locations showing correlation (bottom) and residuals (top).

Figure 4: Comparison of the revised ESI with the WBGT index obtained from 9 different locations showing correlation (bottom) and residuals (top).